Search for the Higgs Boson Using Neural Networks in Events with Missing Energy and b-Quark Jets in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We report on a search for the standard model Higgs boson produced in association with a W or Z boson in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV recorded by the CDF II experiment at the Tevatron in a data sample corresponding to an integrated luminosity of 2.1 fb^{-1}. We consider events which have no identified charged leptons, an imbalance in transverse momentum, and two or three jets where at least one jet is consistent with originating from the decay of a b hadron. We find good agreement between data and background predictions. We place 95% confidence level upper limits on the production cross section for several Higgs boson masses ranging from 110 GeV$/c^2$ to 150 GeV$/c^2$. For a mass of 115 GeV$/c^2$ the observed (expected) limit is 6.9 (5.6) times the standard model prediction.

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The Higgs boson is the last particle of the standard model (SM) of particle physics that remains to be discovered. The existence of the Higgs boson is expected to be the direct physical manifestation of the mechanism that provides mass to fundamental particles [1]. Expectations from electroweak data collected at the Tevatron, LEP, and SLD indirectly constrain the Higgs boson mass to $m_H < 157\ \mathrm{GeV}/c^2$ at 95% confidence level (C.L.) [2]. Direct searches at LEP have excluded $m_H < 114.4\ \mathrm{GeV}/c^2$ at 95% C.L. [3]. Upper limits on the production cross section from searches in the region $110 < m_H < 135\ \mathrm{GeV}/c^2$ remain well above the standard model prediction [2], and greatly benefit from improvements of the experimental sensitivity. In this mass region, $b\bar{b}$ is the main decay mode. The b quarks fragment into jets of hadrons, and the signal can be reconstructed as a resonance in the invariant mass distribution of the two jets. Large multijet backgrounds can be reduced by searching for a Higgs boson (H) with an associated vector boson V ($V = W, Z$).

This Letter presents a search for the standard model VH associated production in events with b-quark jets and large missing transverse energy with data corresponding to an integrated luminosity of 2.1 fb^{-1}. This analysis significantly increases the acceptance for signal with respect to previous Tevatron searches [4,5] and introduces advanced analysis methods. We consider ZH production, where $Z \to \nu\bar{\nu}$ and the neutrinos (ν) escape detection, or $Z \to \ell\ell$ when both charged leptons (ℓ) are undetected or are identified as jets. For WH production we are sensitive to events where $W \to e\nu$ or $W \to \tau\nu$ when the charged lepton is identified as a jet, and $W \to \ell\nu$ when ℓ is undetected. The WH events accepted by this analysis contain 50% $W \to \tau\nu$, 30% $W \to \mu\nu$ and 20% $W \to e\nu$. Critical challenges for this analysis are to achieve a high signal-to-background (S/B) ratio and to model the multijet background production accurately. We employ artificial neural networks (ANNs) [6] to improve the event selection and signal discrimination and implement a novel data-driven determination of the multijet background.

CDF II is a multipurpose detector that is described in detail elsewhere [7,8]. Jets are reconstructed from energy depositions in the calorimeter towers using a jet clustering cone algorithm [9] with a cone size of radius $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$. In addition to standard jet energy corrections [9], we further correct using momentum measurements provided by the tracker, using a method similar to that described in [10]. The more precise measurement of the jet energies improves the candidate Higgs boson mass resolution by $\approx 10\%$ and increases the signal acceptance by $\approx 10\%$. Both the magnitude and direction of $\not\!\!E_T$ are recomputed after the jet energies are corrected.

The events used in this search are selected by a three-level trigger system that selects events with $\not\!\!E_T$ and two jet clusters. After offline reconstruction, the event selection requires $\not\!\!E_T > 50$ GeV, and the transverse energies $E_T^{J_1}$ and $E_T^{J_2}$ of the two jets with the highest transverse energy, J_1 and J_2 ("leading jets"), satisfy the conditions $E_T^{J_1} > 35$ GeV and $E_T^{J_2} > 25$ GeV. We consider an event to have three jets if the E_T of the third leading jet, J_3, is greater than 15 GeV. Events with four or more jets with $E_T > 15$ GeV and $|\eta| < 2.4$ are rejected. Events passing these criteria are denoted as the "pretagged" sample. After these selections, the expected S/B ratio is around 1/20 000.

We veto events with at least one $p_T > 10\ \mathrm{GeV}/c$ isolated electron or muon [11], deliberately using fairly loose identification criteria. These selections ensure that the sample used in this analysis is statistically independent from the one utilized in the search for WH in a final state containing an identified charged lepton [12].

Large backgrounds originating from light-flavor jet production can be reduced by identifying b jets in the candidate events. Because of their relatively long lifetime, b and c hadrons can travel a few millimeters from the primary vertex before decaying into lighter hadrons. Jets originating from a b quark can be identified ("tagged") by the SECVTX algorithm [13], which reconstructs vertices that are significantly displaced from the $p\bar{p}$ interaction point, and the JETPROB algorithm [14], which classifies jets using the probability that tracks within the jet are consistent with originating from the primary vertex. To enhance the expected signal significance we subdivide the sample into three independent categories: events with two jets tagged by SECVTX (SV + SV), events with one jet tagged by SECVTX and another by JETPROB (SV + JP) and events with only one jet tagged by SECVTX (SV).

The selected sample is dominated by background from the production of multijet (MJ), top quark (pair and electroweak production), W or Z plus jets, and WW, WZ or ZZ events. Significant $\not\!\!E_T$ in multijet events appears when b quarks decay semileptonically or when jet energies are mismeasured. In both cases $\vec{\not\!\!E}_T$ is often aligned with $\vec{E}_T^{J_2}$. Therefore, events with $\Delta\phi(\vec{\not\!\!E}_T, \vec{E}_T^{J_2}) < 0.4$, no identified leptons, and $50 < \not\!\!E_T < 70$ GeV are used to measure the rates with which the heavy-flavor jets (HF, originating from a b or c quark) from multijet production and light-flavor jets mistakenly identified as b jets ("mistags") are tagged. The tagging rate (TR) is parametrized as a function of H_T [8] of the event and E_T, η, and ζ of the jet. The observable ζ is defined as $\zeta = c\sum_i p^i_{T,\mathrm{track}}/E_T$ where $p^i_{T,\mathrm{track}}$ includes tracks within a jet with a significant impact parameter and $0.5 < p^i_{T,\mathrm{track}} < 200\ \mathrm{GeV}/c$. Jets originating from b quarks are expected to have a large ζ. The multijet background in the single (double) tagged sample is determined by the probability to tag one (two) jet(s) from the pretagged (single-tagged) sample [11,15], after subtracting all Monte Carlo (MC) simulated contributions. The validity of the tagging rate modeling is verified in various control regions, which are defined below. The remaining backgrounds are estimated using PYTHIA [16] simulations, and single top production is simulated with

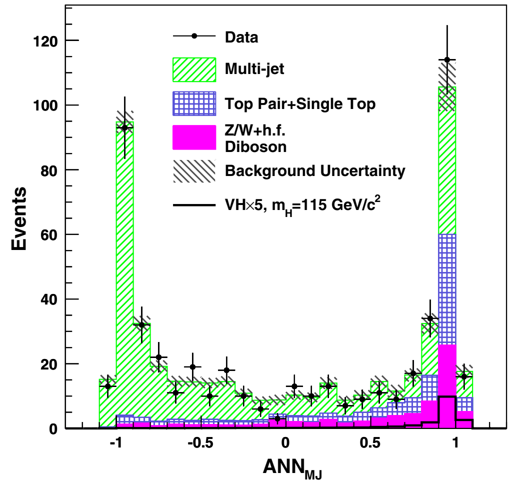

FIG. 1 (color online). The distribution of $\mathrm{ANN_{MJ}}$ for double-tagged events.

MADEVENT [17]. The signal MC samples are generated with PYTHIA. The normalizations of the MC samples are described in [11].

We start the selection of the signal region by requiring no identified charged leptons, $\not\!\!E_T > 50$ GeV, $\Delta\phi(\vec{\not\!\!E}_T, \vec{E}_T^{J_1}) \geq 1.5$, and $\Delta\phi(\vec{\not\!\!E}_T, \vec{E}_T^{J_{2,3}}) \geq 0.4$. These selection criteria remove $\approx 10\%$ of the signal in the pretag sample while reducing the backgrounds by approximately an order of magnitude. We employ an ANN, denoted as $\mathrm{ANN_{MJ}}$, using kinematic variables to separate signal from multijet background. To discriminate against events with $\not\!\!E_T$ due to mismeasurements in the calorimeter, we use the momentum imbalance in the tracker, $\not\!p_T^{\mathrm{tr}}$ [8]. The magnitude of $\not\!\!E_T$ $\not\!p_T^{\mathrm{tr}}$, the angle between them, the azimuthal angles between $\not\!\!E_T$, $\not\!p_T^{\mathrm{tr}}$ and the jet directions, and several other less discriminating variables are used as inputs to $\mathrm{ANN_{MJ}}$ [11]. The distribution of $\mathrm{ANN_{MJ}}$, shown in Fig. 1, peaks at $+1$ for the signal and at -1 for the backgrounds that are due to mismeasured jets. Selecting events with $\mathrm{ANN_{MJ}} \geq 0$ rejects over 50% of the total background and retains 95% of the signal, yielding an S/B ratio of $\approx 1/250$, which is similar to the one obtained in the WH search [12]. This region is defined as the signal region and is analyzed for the presence of the Higgs boson signal.

In order to avoid potential bias in the search, we test our understanding of the SM background in several control regions where the amount of signal events is negligible. The control region called EWK, sensitive to electroweak processes and top production, contains events with at least one lepton and $\Delta\phi(\vec{\not\!\!E}_T, \vec{E}_T^{J_2}) \geq 0.4$. We also define several control regions dominated by multijet processes where we have no identified leptons. The region denoted as MJ1 contains events with $\Delta\phi(\vec{\not\!\!E}_T, \vec{E}_T^{J_2}) < 0.4$ and $\not\!\!E_T \geq 70$ GeV. The region denoted as MJ2 contains events with $\Delta\phi(\vec{\not\!\!E}_T, \vec{E}_T^{J_1}) \geq 1.5$, $\Delta\phi(\vec{\not\!\!E}_T, \vec{E}_T^{J_{2,3}}) \geq 0.4$, and $\mathrm{ANN_{MJ}} < -0.5$. The predictions of the multijet background are tested in MJ1 and MJ2. The distributions of kinematic variables,

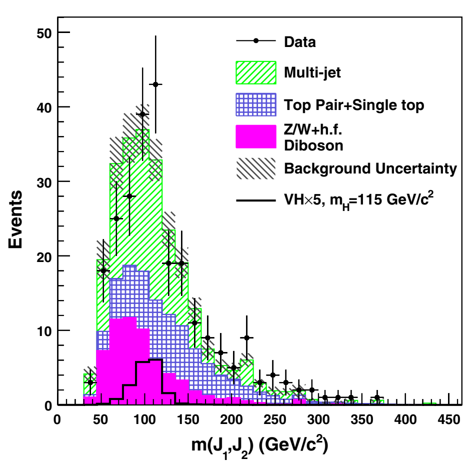

FIG. 2 (color online). Dijet invariant mass distribution for double-tagged events in signal region.

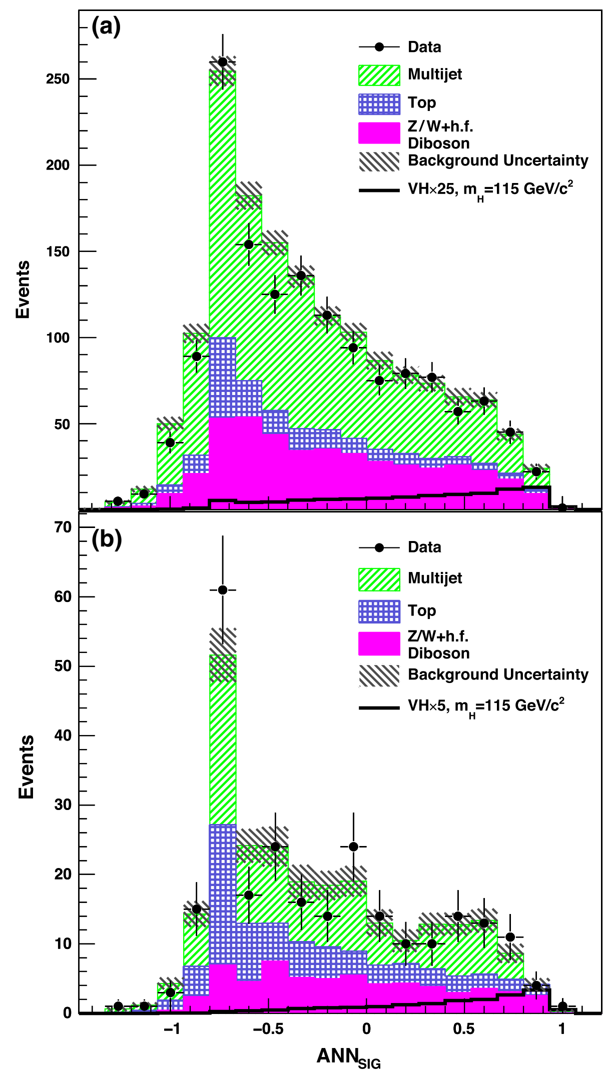

FIG. 3 (color online). The distribution of $\mathrm{ANN_{sig}}$ for (a) single- and (b) double-tagged events.

TABLE I. Comparison of the total number of expected and observed events in the signal region for different b-tagging categories. The uncertainties contain both MC statistical error and systematic uncertainties.

Process	SV + SV or SV + JP	SV
Multijet	120.1 ± 21.3	941.2 ± 86.0
Single top	15.7 ± 3.0	43.2 ± 7.9
Top pair	54.5 ± 7.9	124.5 ± 17.0
Diboson	9.2 ± 1.8	35.6 ± 6.8
W + HF	32.0 ± 14.7	296.9 ± 129.5
Z + HF	22.1 ± 11.5	107.0 ± 45.8
Total prediction	254 ± 39	1548.4 ± 168.1
Observed	253	1443
Expected signal for $m_H = 115\ \mathrm{GeV}/c^2$		
$ZH \to \nu\nu bb$	1.8 ± 0.2	2.1 ± 0.2
$WH \to (\ell)\nu bb$	1.6 ± 0.2	1.8 ± 0.2
$ZH \to (\ell\ell)bb$	0.07 ± 0.01	0.09 ± 0.01

TABLE II. Expected and observed 95% C.L. upper limits, with ratios to SM cross section.

m_H (GeV/c^2)	Expected (pb)	Observed (pb)	Ratio expected	Ratio observed
110	1.3	1.5	$4.9^{+2.1}_{-1.4}$	5.8
115	1.2	1.5	$5.6^{+2.4}_{-1.6}$	6.9
120	1.2	1.5	$7.2^{+2.9}_{-2.1}$	8.9
130	1.0	1.4	$10.3^{+4.3}_{-2.9}$	14.4
140	0.9	1.0	$18.6^{+7.8}_{-5.4}$	21.0
150	0.8	1.0	$43.3^{+19.0}_{-12.4}$	49.8

such as the invariant mass of the two leading jets $m(J_1, J_2)$, have been found to be in agreement with observations in the control regions [11].

To achieve a greater separation between signal and background we deploy a second ANN, denoted as $\mathrm{ANN_{sig}}$, for discriminating the remaining backgrounds from the expected signal. Six input variables are used in $\mathrm{ANN_{sig}}$: the invariant mass of the two leading jets $m(J_1, J_2)$ (Fig. 2), the invariant mass of the $\not{E}_T$ and all jets, $H_T - \not{E}_T$, $\not{H}_T - \not{E}_T$, TRACKMET [18] and the maximum $\Delta R(\vec{E}_T^{J_i}, \vec{E}_T^{J_k})$. The variable TRACKMET is the output of a ANN developed using tracking information to enhance the separation of events with real $\not{E}_T$. The most discriminating variable of the $\mathrm{ANN_{sig}}$ is $m(J_1, J_2)$.

The distribution of $\mathrm{ANN_{sig}}$ is shown in Fig. 3 for single- and double-tagged events. The number of signal and background events after the final selection are shown in Table I. Since no significant excess is observed, we compute 95% C.L. upper limits for the Higgs boson production cross section times the branching fraction $B(H \to b\bar{b})$. For $m_H = 115\ \mathrm{GeV}/c^2$ we expect a total of 4.0 (3.5) signal events with one (two) b-tagged jets [19].

We analyze the binned $\mathrm{ANN_{sig}}$ discriminant distribution to test for a WH or ZH signal in the presence of SM backgrounds. The systematic uncertainties included in the calculation are classified as correlated (uncorrelated) depending on if they do (do not) affect both signal and the background processes [11,18]. The uncorrelated systematic uncertainties are the multijet normalization (between 5.5% and 20.6%) and MC statistical fluctuations. Additionally we assign the following uncertainties due to cross sections: 15.9% and 15.2% to single top in s and t channels, 8.6% to top pair, 11.5% to diboson and 40% to W + HF and Z + HF The shapes obtained by varying the TR probabilities by $\pm 1\sigma$ are applied as systematic uncertainties to each bin of $\mathrm{ANN_{sig}}$. The correlated systematic uncertainties are the following: luminosity measurement (6.0%), b-tagging efficiency in MC simulations (between 4.3% and 12.4%), trigger efficiency (<3%), lepton veto efficiency (2%), parton distribution function uncertainty (2%) and 3.8%–13.0% for jet energy scale (JES) [9]. We also assign systematic uncertainties on the shape of $\mathrm{ANN_{sig}}$ due to JES and trigger efficiency uncertainties. Initial- and final-state-radiation systematic uncertainties (between 1% and 5%) are applied to the signal predictions.

Including all the uncertainties, the expected and observed upper limits at the 95% C.L. on VH production cross section times branching fraction $\mathrm{Br}(H \to b\bar{b})$ are shown in Table II. Expected limits are obtained by generating pseudoexperiments from the expected SM $\mathrm{ANN_{sig}}$ shapes to calculate the median ZH and WH contribution which could be excluded at the 95% C.L. in the zero signal hypothesis. The limits are computed using the Bayesian likelihood method [20] with a flat prior probability for the signal cross section and Gaussian priors for the uncertainties on acceptance and backgrounds. We combine the search channels SV + SV, SV + JP, and SV by taking the product of their likelihoods and simultaneously varying the correlated uncertainties. The observed limits agree with the expected ones.

In summary, we have performed a direct search for the SM Higgs boson decaying into b-jet pairs using data with integrated luminosity of 2.1 fb^{-1} accumulated in Run II by the CDF II detector. The combination of all improvements described above increases the sensitivity of this search by a factor of 2 with respect to [4], and by 30% with respect to [5] once the difference in luminosity is accounted for.

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